Electron Bunch Profile Diagnostics in the Few fs Regime using Coherent Smith-Purcell Radiation

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ELECTRON BUNCH PROFILE DIAGNOSTICS IN THE FEW FS REGIME USING COHERENT SMITH-PURCELL RADIATION

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Abstract

The rapid developments in the field of laser-driven particle acceleration hold the prospect of intense, highly relativistic electron bunches that are only a few fs long. The determination of the temporal profile of such bunches presents new challenges. The use of a radiative process such as Smith-Purcell radiation (SPR), is particularly promising in this respect. In this technique the beam is made to radiate a small amount of e/m radiation and the temporal profile is reconstructed from the measured spectral distribution of the radiation. We summarise the advantages of SPR and present the design parameters and preliminary results of the experiments at the FACET facility at SLAC. We also discuss a new approach to the problem of the recovery of the 'missing phase', which is essential for the accurate reconstruction of the temporal bunch profile.

INTRODUCTION

New diagnostics techniques for the measurements of electron bunch length and longitudinal profile in the few fs regime are required for the characterisation of electron bunches in advanced accelerators such as high brightness drivers for fourth generation light sources [1], or in laser plasma accelerators [2] or beam driven plasma accelerators [3].

Several techniques have been developed for this purpose. Transverse deflecting cavities (TDC) have proven to be capable of bunch profile measurement in the few fs range [4]. They are, however, invasive. Electro-optic sampling (EOS) has also been successfully used in the tens of fs regime [5]. However it remains to be proven that the resolution of the method can be extended to few fs regime. A number of other techniques exploit coherent radiative processes such as coherent optical transition radiation (COTR) [6] or coherent Smith-Purcell radiation [7] for beam diagnostic purposes. We propose to exploit the intrinsic dispersive characteristic of the Smith-Purcell radiation to provide a diagnostic method which is non-invasive, economic, single shot, high resolution and can provide bunch length and profiles measurements down to the few fs FWHM regime.

Coherent Smith-Purcell (CSP) radiation has been proposed as a diagnostic tool for bunch length and bunch profile measurements for increasingly shorter bunches, by the Oxford group since the early 90s [8]. The experimental results obtained in 2007 at SLAC End Station A (ESA) proved that this technique is capable of measuring bunch length and profile in the order of a few ps FWHM [9].

Recent theoretical and numerical work has shown that this technique can be extended to the measurements of significantly shorter bunch lengths and profiles [10]. Furthermore significant progress has been made in the analysis of the measured spectra addressing the issues related to the missing phase information [11].

Underpinned by these studies, we have recently been awarded beam time at the SLAC Facility for Advanced Accelerator Experimental tests (FACET) [12] to test the technique. FACET can deliver an electron beam of variable bunch length down to 140 fs FWHM and it is an ideal test bed for SPR diagnostics in the fs regime. The Smith-Purcell experiment was installed in August 2011 and commissioning beam time has been available in the last two weeks of August. In this initial stage, our experiment is also aiding the re-commissioning of the FACET facility. Despite the early stages of operation we were able to detect Coherent SPR and provide first preliminary estimates of the bunch length and profiles. FACET is scheduled to provide beam time to users starting in March 2012.

COHERENT SMITH PURCELL RADIATION AS BEAM DIAGNOSTICS

Smith-Purcell radiation is emitted by an electron beam passing near the surface of a metallic grating. The radiation emitted by a single particle has characteristic dispersive properties. In the far field, the wavelength λ is related to the observation angle θ, measured from the direction of the beam, by the equation

$$\lambda = \frac{\mathrm{L}}{\mathrm{n}}\left(\frac{1}{\beta} - \cos\theta\right)$$

where L is the period of the grating, n is the order of the radiation and β is the velocity of the particle in units of c. The angular distribution of the emitted energy at the order n, in the case of an infinitely wide grating, is given by [8]

$$\frac{\mathrm{dI_n}}{\mathrm{d}\Omega} = 2\pi \mathrm{e}^2 \frac{\mathrm{Z}}{\mathrm{L}^2} \frac{\mathrm{n}^2\beta^3}{(1-\beta\cos\theta)^3} \mathrm{R}_\mathrm{n}^2 \exp(-2\mathrm{x}_0/\lambda_\mathrm{e})$$

where R_n is the grating efficiency factor, x_0 is the height of the beam above the grating, φ is the angle of rotation along the beam axis and

$$\lambda_\mathrm{e} = \lambda \frac{\beta\gamma}{2\pi\sqrt{1+\beta^2\gamma^2\sin^2\theta\sin^2\varphi}}$$

where γ is the electron relativistic factor.

When a bunch of electrons is considered, the spectral distribution of the Smith-Purcell radiation is coherently enhanced at the wavelengths which are larger than the bunch length. In this regime the angular distribution of the emitted energy is given by

$$\left.\frac{dI_n}{d\Omega}\right|_{N_e} \propto \left.\frac{dI_n}{d\Omega}\right|_1 N_e^2 S_{coh}$$

where N_e is the total number of electrons in the bunch and S_{coh} is the enhancement proportional to the bunch form factor, i.e. the square modulus of the Fourier transform of the longitudinal profile f(t) of the bunch.

We can not however measure the phase of the spectrum, leaving only partial information for the reconstruction of the longitudinal profile. The problem of the missing phase can be tackled with different numerical techniques. In the past we have developed a reconstruction technique based on the Kramers-Kronig (KK) relations, which provide the minimal phase compatible with the measured spectrum. It was realised however that the KK relation fails to reconstruct profiles with complicated structures such a double horned pulses. Therefore a new technique for the reconstruction of the missing phase is currently being investigated. This is based on the difference map algorithm [13] and is the basis for modern phase reconstruction techniques commonly used in protein crystallography to reconstruct the spatial structure of an object form its diffraction pattern. Our technique can be seen as a simple 1D version of such techniques, applied to the reconstruction of the longitudinal profile of the electron bunch. More details can be found in [11]. Numerical experiments showed that this technique is capable of reconstructing correctly some of the profiles where the KK method fails. It does however not provide a unique answer in all cases.

EXPERIMENTAL APPARATUS

The experimental apparatus consists of a vacuum chamber which hosts a set of gratings and holds the SPR detection system on its outside. The layout of the chamber is shown in Fig. 1.

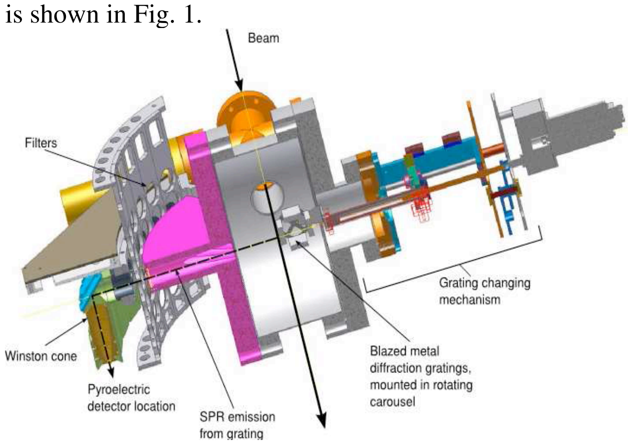

Figure 1: Layout of the Smith-Purcell vacuum chamber.

The beam enters the chamber and travels past a metallic grating. The position of the grating with respect to the beam axis can be varied remotely. In order to cover a sufficiently large spectral range for an effective reconstruction of the coherent SPR spectrum, three gratings with different periods, chosen to match the expected bunch length range, are used one at a time. For this purpose a carousel mechanism allows the positioning of the three gratings and one flat blank, used to determine the background radiation. For the FACET experiments, we chose gratings optimised for a 140 fs FWHM electron bunch. Numerical simulations showed that the combination of grating periods 50 μm, 250 μm and 500 μm is suitable for this purpose.

Eleven detectors are located away from the gratings and cover emission angles from 40^0 to 140^0 with respect to the direction of propagation of the beam. The coherent SPR reaches each detector via its own silicon vacuum window. The aperture of the window is circular and subtends an azimuthal angle $\theta = \pm 6^0$ from the grating centre. The contribution of this aperture is fully taken into account in the computation of the power of the radiation measured by the detector. The coherent SPR travels through the vacuum windows and a filter appropriate for the angle of observation and the grating period used and is focussed on a pyroelectric detector by a Winston cone. The set of filters used varies according to the wavelength detected and they are either waveguide array plates (WAP) for longer wavelengths (175 μm < λ < 1mm) or Mylar or silicon foils for shorter wavelengths (10 μm < λ < 120 μm). The filters are mounted on an array made of six rows of eleven circular supports. In this way for each grating we can remotely select the correct set of eleven filters for each grating used. The first three rows of filters have a bandwidth which corresponds to the coherent SPR expected for the FACET bunch, while the remaining three rows of filters were used to check polarisation and background issues. The transmission of the filters obtained from the manufacturers was used in the computation of the detection efficiency of the channels. Data were also corrected to account for windows transmission, Winston cones efficiency, grating efficiency, beam position over the grating and beam charge. Furthermore, the pyroelectric detectors were carefully calibrated at the wavelength of interests using the B22 IR beamline at the Diamond Light Source.

The signal received by the pyroelectric detectors is acquired and digitised by a DAQ system which is triggered by the linac trigger. A time span of 80 μs is sampled at 2.5 μs sampling rate for a total of 32 samples per acquisition. The acquisition window is adjusted such that the first half of the data is taken before the passage of the bunch and the second half after. The rise time of the pyroelectric detector is about 2.5 μs: the difference between the averages of the first half of data and the second half is taken as a measure of the power radiated by the bunch to the corresponding detector. The background intensities, as measured by the blank in the same position, are subtracted from this signal.

EXPERIMENT AT FACET

FACET offers the possibility of testing the CSP technique on the 20 GeV electron beam delivered by the first 2/3 of the linac. The FACET experimental area is located at the end of the 2/3 of the linac and hosts several experiments [12]. The linac is operated at 10 Hz or less and generates a single bunch with a charge variable up to 3 nC. The bunch compressor in Sector 20 allows a flexible control of the bunch length down to a design minimum of 140 fs FWHM or below. The facility has been re-commissioned with beam at the beginning of August 2011 and has delivered first beam to the experiments in the second half of August. Although the beam quality was not the nominal achievable, we could operate with bunches of the order of few hundreds of fs in the early stage of the commissioning. The optics of the linac were set to have a waist to few tens of µm close to the Smith-Purcell vacuum chamber, mainly due to the need of concomitant experiments. In fact the Smith-Purcell experiment is relatively insensitive to the transverse size of the beam, provided it does not have large halos that increase the background as the grating intercept it. The full machine data were available although not yet fully synchronised with the Smith Purcell signals acquisition. In particular we recorded the charge, the beam positions at the BPMs immediately upstream and downstream of the Smith Purcell vacuum chamber. No absolute alternative measurement of the bunch length was available to provide an independent check on the bunch length. The information on the relative length was obtained from a pyroelectric detector which was routinely used for relative bunch length measurements.

EXPERIMENTAL DATA AND ANALYSIS

In the last two weeks of August a number of runs dedicated to the Smith-Purcell experiment were made. It was possible to detect Smith–Purcell radiation and then test different beam conditions, varying the position of the beam and the bunch length. The signal was recorded from the DAQ for each detector.

Two typical spectra recorded from the grating with period 500 µm are shown in Fig. 2. The quality of the signal recorded was sufficiently good to perform a preliminary time profile analysis. The profiles extracted from these data are shown in Fig. 3. The shortest time profile of the electron bunch is about 350 fs FWHM. Changing the compressor settings stretched the bunch to about 600 fs. In Fig 4 we show that the FWHM measured by the reconstruction of the coherent SPR spectrum is well correlated with the independent relative bunch length information obtained with FACET's pyroelectric detector. Bunch lengths in this range are what is currently achievable at FACET. More data will be taken in the next run in 2012 when shorter bunch lengths are expected to be available.

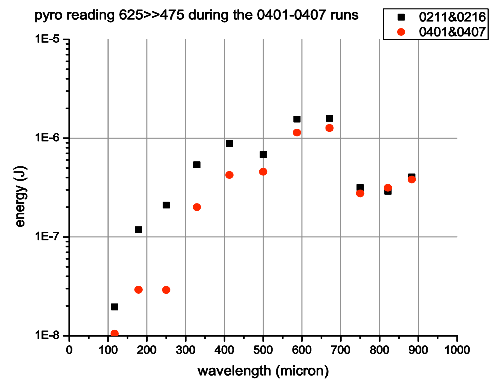

Figure 2: Spectrum for a single grating of 500 µm.

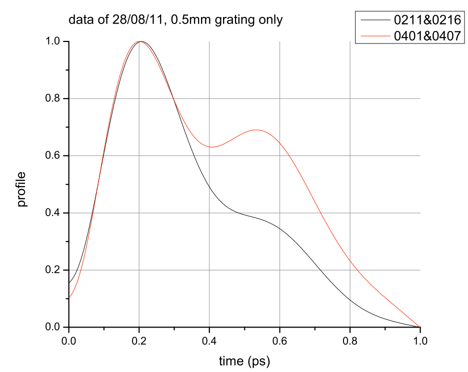

Figure 3: Preliminary profile reconstruction of a FACET beam from the coherent SPR spectra detected in Figure 2.

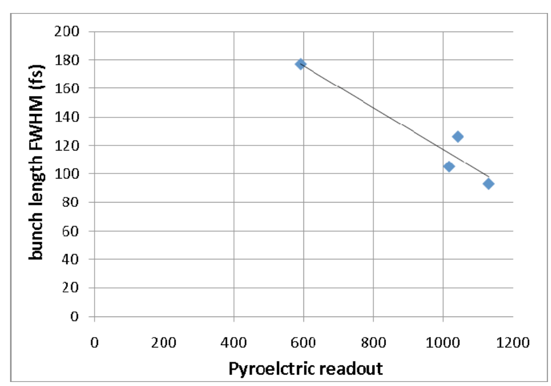

Figure 4: Preliminary correlation of FWHM with pyroelectric readout.

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